The Introduction of the Loading Coil: George A. Campbell and Michael I. Pupin

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The introduction of loading coils into telephone circuits was probably the most important single technical innovation in telephony during the forty-year period between the time of Bell's original inventions and the introduction of electronic amplifiers. By 1900 long-distance telephony had reached what seemed to be a practical limit in a 1,200-mile circuit between Boston and Chicago. The loading innovation, in effect, doubled the practical distance and also led to substantial reductions in the construction costs of underground cable circuits used in urban areas. Exploitation of the loading coil saved the American Telephone and Telegraph Company an estimated one hundred million dollars during the first quarter of the 20th century.[1] Despite its great economic importance and the fact that it has been frequently cited to illustrate the impact of science on technology, the early history of the loading coil has been subject to considerable misunderstanding. This is due not only to the somewhat esoteric nature of the innovation but also to a persistent myth regarding the role of Michael I. Pupin in its introduction.

The coil-loaded telephone circuit may seem deceptively simple, since it consists of inductance coils connected in series with the conductors of telephone wires at periodic intervals. However, an examination of the historical details reveals that this was one of the most sophisticated electrical innovations of the 19th century. It is significant that each of the claimants to priority of discovery was proficient in mathematical physics. Unlike earlier communications advances, even including the telephone itself, loading was based on an understanding of the Maxwell-Heaviside electromagnetic theory and required an "inventor" having a considerable facility in applying

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[1] Thomas Shaw and William Fondiller, "Developments and Applications of Loading for Telephone Circuits," *Transactions of the American Institute of Electrical Engineers* 45 (1926):291–92 (hereafter cited as *Trans. AIEE*).

and extending that theory. Consequently, it is not surprising to find that many engineers and patent specialists experienced difficulty in grasping some of the subtleties of the analysis and explanation of loading. The successful practice of loading required that strict limits be placed on the design and spacing of the loading coils. If these limits were not satisfied, transmitted currents were subjected to more distortion than if loading had not been used at all. Also, inductance coils had often been used in other applications to impede rather than enhance the transfer of alternating-current energy. For this reason, many engineers were not convinced that loading would really improve telephonic transmission until they had witnessed demonstrations on actual circuits.

Many important technical inventions or discoveries have been controversial, and loading was no exception. Michael I. Pupin, a Columbia University professor, won both fame and a considerable fortune for his role in the introduction of loading. Pupin's version of the history of the loading coil was included in his autobiography, *From Immigrant to Inventor*, which won him a Pulitzer prize in 1924. This version seems to have been generally accepted by recent historians of electrical technology.[2] A second claimant was the brilliant and eccentric British electrical theorist, Oliver Heaviside. A few of Heaviside's advocates argued that the Bell company had conspired to deny him the credit for this and other discoveries.[3] A third and probably the least-known

[2] See, for example, Harold I. Sharlin, *The Making of the Electrical Age* (London, 1963), pp. 65–68, and Percy Dunsheath, *A History of Electrical Engineering* (London, 1963), p. 245.

[3] For example, B. A. Behrend wrote to G. F. C. Searle, a British scientist and friend of Heaviside, that he had succeeded in persuading the directors of the American Institute of Electrical Engineers to award an honorary membership to Heaviside only by agreeing to give support to "the recognition of certain parties by the award of an Edison Medal." Presumably, Behrend was alluding to John J. Carty, chief engineer of the American Telephone and Telegraph Company, who was awarded the Edison Medal in 1918 while Behrend was a member of the Edison Committee. Behrend also informed Searle that "certain interests" had tried to persuade him to act as intermediary in offering Heaviside a few thousand dollars in belated recognition for the importance of his contribution to communication technology. Searle had suggested that a Cambridge chair be endowed by contributions from industry in honor of Heaviside, but Behrend opposed this being done "by the very people who destroyed his life and prevented his recognition." Norbert Wiener, another Heaviside advocate, wrote Behrend in 1931 to thank him for a guide to his collection of "Heavisidiana" and added that it was being photostated for "antipupinian" friends. See Behrend to Searle [?] 1928, and Wiener to Behrend [?] 1931, Behrend Papers, Clemson University Archives, Clemson, S.C. Wiener later wrote what appears to be

claimant was George A. Campbell, an engineer with the American Bell Telephone Company. Despite his comparative obscurity, the evidence indicates that Campbell was the first to load actual telephone circuits successfully and that his theoretical analysis of loading formed the basis for subsequent loading practice by the Bell company.

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The three claimants mentioned had very dissimilar personalities and professional affiliations. As a young man, Heaviside had been employed briefly as a telegrapher but never again accepted employment after retiring in 1874 at the age of twenty-four. He came to consider himself as an interpreter and extender of the energy transmission theory of Maxwell for the benefit of telephone and telegraph engineers, and he published frequently in engineering and scientific journals. Heaviside never attended meetings of professional societies, although he corresponded with many leading scientists and engineers. He was eager to receive credit for what he considered to be his intellectual property, although he apparently made no effort to patent any of his many suggested innovations in communications technology.

Pupin was a flamboyant and gregarious individual. He was active in the affairs of the American Institute of Electrical Engineers and published frequently in its *Transactions*. Pupin became his own best publicist and, unlike Heaviside, proceeded to take full advantage of the patent system. Most of his experimental work was carried out with the aid of his students in a small basement laboratory at Columbia. From the sale of the rights to a small number of electrical patents, Pupin achieved a financial success which has seldom, if ever, been equaled by a full-time engineering professor.

Campbell was a member of the engineering staff in the Boston

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a fictional version of the "conspiracy" against Heaviside. See Norbert Wiener, *The Tempter* (New York, 1959).

Heaviside himself claimed credit for the invention in his essay on telegraphy included in the tenth edition of the *Encyclopaedia Britannica*. See Oliver Heaviside, *Electromagnetic Theory* (New York, 1950), p. 343 (this is an unabridged reprint of the edition originally published in three volumes in 1893, 1899, and 1912, respectively). Heaviside also discussed the priority question in a letter to Behrend in 1918. Heaviside wrote that no one had questioned his priority until Pupin sold his patents, but that, following that event, a great change had occurred and he (Heaviside) had been "repudiated in a most emphatic manner." Heaviside suggested that commercial considerations had been responsible for the change, since "prior publication . . . if admitted, might have interfered with the flow of dollars in the proper direction and have led to much trouble and expense." See Heaviside to Behrend, February 20, 1918, Heaviside Papers, Institute of Electrical Engineers, London.

laboratory of the American Bell Telephone Company. He was an intellectual introvert with a dislike for administrative duties. Unlike Pupin, he was never active in professional societies and published comparatively little in technical journals.[4] Although he remained almost unknown outside the telephone company, Campbell was the company's leading electrical theorist for many years and was responsible for the introduction of several of the most important innovations in modern communications technology.[5]

Guided by his study of Maxwell's *Treatise on Electricity and Magnetism*, Heaviside by 1881 had arrived at a differential equation for the analysis of uniform transmission lines in terms of four distributed line parameters.[6] In 1887 Heaviside announced his discovery of a criterion for "distortionless transmission." His theory indicated that the product of resistance and capacitance of a circuit should be made equal to the product of leakage and self-induction for minimum transmission distortion. Since the product of resistance and capacitance was much larger on normally constructed circuits, Heaviside pointed out that transmission quality should be improved if either the leakage or self-induction were to be artificially increased. He suggested that

[4] This was at least partly due to the general policy of the company, during Campbell's early years in Boston, of not encouraging the publication of results of current research which might be of use to independent competitors. The first report of Campbell's theoretical and experimental work on loading did not appear in a technical journal until approximately four years after it had been done. This paper and a few of his previously unpublished early reports on loading research were included in a volume of his collected papers published in 1937 on the occasion of his retirement. See *The Collected Papers of George Ashley Campbell* (New York, 1937). The policy of secrecy was evidently somewhat modified by 1904. An editorial in the *Electrical World and Engineer* early in 1904 commented on the first paper by Campbell to be published in that journal. The editor stated that Campbell's paper was important both because of its technical content and because it indicated a policy change on the part of the Bell system. The editor suggested that the company's previous po'icy had been "short sighted, imprudent, and immoral." He argued that, while the company had the right to withhold trade secrets and manufacturing data, it should not keep secret matters related to general technology or applied science "which, if made known, only redound to the credit of the industry disclosing while adding to the world's general stock of knowledge." He continued that, if important discoveries were kept secret and later discovered by outsiders, "the original work done earlier by the industry has lost credit, and has lost the evidence of progress" (*Electrical World and Engineer* 42 [1904]:633).

[5] Frank B. Jewett, "Dr. George A. Campbell," *Bell System Technical Journal* 14 (1935):553–57.

[6] See Oliver Heaviside, *Electrical Papers*, 2 vols. (Boston, 1925), 1:139–40 (this is an unabridged reprint of the original edition published in 1892). The four parameters were resistance, capacitance, leakage, and self-induction.

an increase in self-induction seemed preferable, since an increase in leakage would result in greater attenuation despite the predicted reduction in signal distortion. One way to increase self-induction was to increase the spacing of wires in a given circuit. Another possibility which Heaviside suggested as worthy of experimental investigation was to employ a dielectric material containing iron dust for insulation in telephone cables.[7]

In 1893 Heaviside suggested that the effective self-induction of a transmission circuit might be increased by the insertion of discrete coils in series with the circuit conductors at periodic intervals. He admitted, however, that there was as yet no experimental evidence that this would prove successful.[8] To his great disappointment, these suggested methods for improving transmission were largely ignored by British telephone engineers. One writer later attributed the neglect to Heaviside's failure to provide "such detailed instruction as to compel the attention of practical telephone engineers."[9] The instructions needed for the effective use of loading coils were the coil design specifications and the optimum coil spacing in terms of the shortest wavelengths of interest in telephony. There is no evidence that Heaviside undertook the analytic or experimental work which would have been required to provide such instructions, perhaps because he was not interested in obtaining patents and felt that such details could best be worked out by telephone engineers using actual circuits. Despite the omission of engineering details, Heaviside had set the stage for the loading coil innovation by his demonstration of the theoretical advantages of increased self-induction in transmission circuits.

John S. Stone, an engineer employed by the American Bell Telephone Company during the 1890s, was apparently the first engineer consistently to apply Heaviside's transmission theory to the practical problems encountered in telephony.[10] In 1897 Stone was granted a

[7] Ibid., 2:123–24.

[8] Heaviside, *Electromagnetic Theory*, p. 112.

[9] See J. A. Fleming, *The Propagation of Electric Currents in Telephone and Telegraph Conductors* (New York, 1911), pp. 108–9.

[10] Stone was one of the first men with a university-level education in science and mathematics to be employed as an engineer by the American Bell Telephone Company. He enrolled at the School of Mines at Columbia in 1886 but transferred to Johns Hopkins University in 1888. Through the influence of Gardner G. Hubbard, a friend of the Stone family and one of the original financial backers of A. G. Bell, Stone was able to spend the summer of 1889 in Paris as an assistant to W. D. Sargent, who was in charge of the American Bell company's exhibition at the Paris Ex-

patent on a proposed new telephone cable which was to use bimetallic wire of iron and copper to give a higher self-induction than available in standard cable.[11] Although Stone's patent made no explicit mention of beneficial effects on transmission other than through the elimination of reflections, he was fully aware of the potential use of a high-induction cable to achieve low-distortion transmission.[12] At Stone's request, the director of the laboratory, Hammond V. Hayes, authorized further research to determine whether bimetallic circuits could be used to obtain a useful improvement in distance and transmission quality.[13]

Campbell's work on the loading coil innovation was a direct outgrowth of the bimetallic cable investigation. When Stone left the company early in 1899, Campbell was assigned to continue work on the high-induction cable.[14] However, Hayes extended the scope of the original work order and authorized Campbell to proceed in any direction which seemed promising. Since no experimental work had so far been done on a long bimetallic circuit, Campbell decided to undertake some preliminary transmission tests for comparison with results obtained on circuits currently being used. The cost of an actual bimetallic circuit of the length needed for conclusive results would have been large, whereas the funds available for research on

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position. Stone was hired after his graduation the following year. See George H. Clark, *The Life of John Stone Stone* (San Diego, Calif., 1946), pp. 14–26.

[11] Stone's patent was no. 578,275, issued March 2, 1897. The claims in the patent were confined to the use of the new cable to eliminate wave reflections at junctions with high-impedance overhead lines. Heaviside had shown that this would be accomplished if the ratio of self-induction to capacitance of a cable were made equal to that of the overhead line.

[12] Stone had attempted to calculate the degree of improvement which might potentially be achieved by means of a high-induction cable and had discussed the problem in personal correspondence with Heaviside in 1894. See Stone to Heaviside, May 12, 1894, Heaviside Papers.

[13] See the *Record for George A. Campbell,* Interference no. 20,699 (Boston, 1902), pp. 9–10. (Hereafter cited as *RGAC.*)

[14] Campbell had received a bachelor's degree in engineering at the Massachusetts Institute of Technology in 1891. He had then spent two years at Harvard, where he received a master's degree in 1893. He was then awarded a fellowship which enabled him to spend a year at Göttingen, where he studied advanced mathematics under Felix Klein, a year at Vienna, where he studied electricity and mechanics under Boltzmann, and a year in Paris, where he studied under Henri Poincaré. Campbell was awarded a doctorate at Harvard in 1901, his dissertation being based on his research on loading coils at the Bell laboratory. See *RGAC,* pp. 4–5.

the project were quite limited.[15] In the interest of maximum economy, Campbell proposed the construction of an artificial transmission line which would serve to simulate an actual circuit for his preliminary tests.[16]

In the process of working out the design of the artificial line, Campbell asked himself what proved to be a crucial question. If one could use discrete inductance coils to simulate distributed inductance in an artificial line, might it not also be possible to use similar discrete inductors periodically spaced along an actual line? If so, this would make possible a much greater increase in the effective line inductance than seemed to be theoretically possible using Stone's bimetallic cable design.[17] Excited by the new idea, Campbell immediately abandoned further work on bimetallic circuits and turned his attention to what soon became known as the loading coil. Campbell's familiarity with the Heaviside transmission theory and an extraordinary mathematical ability enabled him to make rapid progress in working out the engineering details needed for a full-scale experiment with a loaded telephone circuit.

The most important immediate problem which Campbell faced was to determine the maximum allowable interval between coils, since the ultimate practical value of the innovation would largely depend on this factor. His preliminary calculations indicated that approximately ten coils per wave at the maximum telephonic frequency employed would be sufficient. This meant that loading coils could be added to the existing underground cable system, since there were normally several manholes per mile. Hayes was especially impressed by this possibility when he discussed the progress of the investigation with Campbell early in 1899. At the request of Campbell, who now wished to test the effect of loading on a standard commercial cable, Hayes arranged to have three reels of the so-called Pittsburgh cable

[15] In a progress report written in July 1899, Campbell stressed the need for economy, since a single experimental setup would probably exhaust the entire project appropriation. See ibid., p. 58.

[16] Artificial transmission lines normally consist of a large number of discrete inductors and capacitors connected in an iterative circuit. The advantage of this transmission structure, in addition to its economy, is that it requires a comparatively small amount of laboratory space. However, considerable care is required both in the manner of construction and in the test procedure employed if the results are to be correlated with the performance of an actual line being simulated.

[17] Although he was familiar with the advocacy of high line self-induction by Heaviside and Stone, Campbell stated that he was not at the time aware that the use of discrete inductors to achieve the increase had already been discussed by Heaviside. See *RGAC*, pp. 12–13.

sent to the Boston laboratory.[18] After Campbell had worked out the design specifications for the loading coils to be used in the proposed tests, an order for 400 of them was placed with a local manufacturing company.[19]

While waiting for delivery of the loading coils, Campbell continued his theoretical work. He succeeded in deriving a general formula for loaded lines which became known as "Campbell's equation." His equation may be written[20]

$$\cosh \gamma' d = \cosh \gamma d + \frac{z}{2z'} \sinh \gamma d, \qquad (1)$$

where γ' is the propagation constant of a loaded line, γ is the propagation constant of the same line without loading, d is the interval between coils, z is the loading coil impedance, and z_0 is the characteristic impedance of the line without loading. This equation was immediately used by Campbell and his assistants to make numerical calculations over a range of assumed loading conditions on standard telephone cables. The results were presented in the form of detailed graphs which clearly showed the optimum coil values and spacing. These graphs were included in a report prepared by Campbell dated July 18, 1899, and entitled "Statement of Progress on Cable Problem."[21] Another report, entitled "On the Introduction of Inductance on Telephone Lines: Description of Loaded Lines for Examination into Patent Claims," was submitted by Campbell the following day.[22] However, Hayes decided that it would be best to wait until

[18] This was called the Pittsburgh cable because it had been used in transmission tests in Pittsburgh. It consisted of standard 19-gauge cable pairs. Connection of the pairs in series provided a circuit with a total length of 35 miles. See *RGAC*, pp. 38–40.

[19] Ibid., p. 42.

[20] For a copy of four pages of Campbell's original notes containing the derivation of his equation, see *RGAC*, pp. 313–16.

[21] Ibid., pp. 57–58, 319–20. In addition to being the first graphs to show the effect of various degrees of loading on attenuation, these were probably the first clearly to depict the cutoff phenomenon which is characteristic of electrical filter networks as well as periodically loaded transmission lines. The loaded lines were found to exhibit a sharp rise in attenuation as the transmitted frequency approached the characteristic cutoff frequency determined by the amount of loading added. Campbell's analysis showed that this critical condition was reached at a frequency of 11,000 cycles per second for the loading used on the Pittsburgh cable. This was reduced to approximately 2,000 cycles per second on some later circuits which were more heavily loaded.

[22] *RGAC*, pp. 58–59.

the tests had been made on the Pittsburgh cable before contacting the company's patent attorney.[23]

The first successful tests ever made on a coil-loaded telephone cable were carried out by Campbell and his assistant, Edwin H. Colpitts, on September 6, 1899.[24] These tests were made using loading coils on the Pittsburgh cable in the Boston laboratory. Campbell and Colpitts were able to carry on a conversation over a 46-mile circuit with a transmission quality equivalent to that of a 23-mile circuit without loading. The tests were repeated the following day for the benefit of Hayes and others in the laboratory. Campbell's theoretical calculations were completely confirmed by these experiments, which demonstrated for the first time that the use of loading coils on standard telephone circuits could achieve an important improvement in distance for a given transmission quality or in quality at a given distance.[25]

Hayes was now convinced that Campbell had made a potentially valuable discovery. He wrote to the company president, John E. Hudson, to inform him of Campbell's results and to request that the use of loading coils be investigated for patentability by the company's patent attorney, William W. Swan.[26] Shortly afterward Campbell was assigned to help Swan in the preparation of a patent application. However, there was a long delay before the application was finally submitted in March 1900. When questioned about the reason for the delay, Campbell later explained it had been necessary for him to spend a considerable amount of time in attempting to explain the loading graphs in his July report to Swan. He stated that they had also undertaken an extensive survey of the relevant literature, including American and foreign patents. Finally, Swan had insisted that the patent specification not contain mathematical formulas but that it be written "in language which would be at once understood by telephone engineers." The subsequent history of the patent application indicates that both the delay in applying and the total deletion of graphs and equations from the application were prejudicial to Campbell's attempts

[23] This delay, in conjunction with the long delay in filing after the Pittsburgh cable tests, made his attempt to establish priority over Pupin's work far more difficult, since the first applicant in a disputed case enjoyed certain procedural advantages.

[24] Colpitts had been hired as Campbell's assistant in 1899. He had completed three years of graduate study in physics and mathematics at Harvard and held a master's degree. See *RGAC,* pp. 171–72.

[25] Ibid., p. 50.

[26] For a copy of the letter from Hayes to Hudson dated September 11, 1899, see *RGAC,* p. 253.

to establish the priority of his work. The technical details contained in his reports prepared in July 1899 were of fundamental importance for the successful introduction of loading.[27]

After Campbell's impressive demonstration of loading on the Pittsburgh cable, Hayes and his engineering staff prepared to exploit the discovery even before the patent application was filed. One member of the staff, Chester H. Arnold, was assigned to carry out a study of the potential advantage of loading a circuit from an economic standpoint.[28] Arnold's calculations indicated that the probable saving in construction costs of new installations proposed in New York and New Jersey alone would amount to approximately $700,000 if loading were used.[29] The first loaded circuits open to public use were two circuits connecting Jamaica Plains and West Newton, suburbs of Boston. These circuits were loaded under Campbell's direction and were first opened to commercial traffic on May 18, 1900.[30] Only six days before, Campbell received from the patent examiner a notification of a rival applicant for a loading coil patent. The rival applicant was Michael I. Pupin.[31]

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Pupin had filed an application for a patent on loading in December 1899. Nearly a quarter of a century later, he wrote an account of his discovery and its significance in his autobiography. It is somewhat surprising that this version has been so widely accepted by historians,

[27] See *RGAC*, pp. 71–72. It is also possible that this was an example of "incomplete disclosure" wherein essential information was deliberately withheld. Whether this was a factor in Swan's insistence on deleting mathematics and graphs has not been determined. For a discussion of the practice of incomplete disclosure, see Floyd L. Vaughan, *The United States Patent System* (Norman, Okla., 1956), p. 218.

[28] Arnold had been with the Bell company since 1893. He had been a classmate of Campbell at Harvard and held a master's degree. See *RGAC*, p. 213.

[29] For a copy of Arnold's report dated January 2, 1900, see ibid., pp. 223–24.

[30] Ibid., p. 66.

[31] Ibid., pp. 268–69. Pupin had arrived in America in 1874 as a sixteen-year-old immigrant from Serbia. After working for several years as a farm laborer and in a cracker factory, he had enrolled at Columbia University, where he received a bachelor's degree in 1883. During the following year, Pupin studied mathematics at Cambridge, England, under John E. Routh. He was then awarded the Tyndall fellowship, which enabled him to study at the University of Berlin under Helmholtz and G. R. Kirchhoff. Pupin was awarded a doctorate at Berlin in 1889 and then accepted a teaching position in the newly created department of electrical engineering at Columbia. See *The Dictionary of American Biography* (New York, 1944), 21:611–15.

since personal memoirs written long after the events described have so often proved to be unreliable as historical sources. In this instance, a comparison of the version in Pupin's book with available contemporary sources reveals a number of distortions and omissions in Pupin's account, which contributed to the growth of a persistent myth depicting Pupin as one of the heroic electrical inventors. Pupin's contributions to the electrical engineering profession as an educator and popularizer of the use of mathematical analysis of alternating-current phenomena were not unimportant. However, the value of these contributions has been largely overlooked because of the notoriety surrounding his electrical "inventions."

In his book, Pupin wrote that the idea of the loading coil invention had first occurred to him while climbing a mountain in Switzerland during the summer of 1894. He stated that he had been preparing lectures on the theory of sound, to be given at Columbia the following fall, and that the idea of loading had been stimulated by his reading of the problem of a vibrating string in Lord Rayleigh's treatise, *The Theory of Sound*.[32] According to Pupin, he had conducted some experi-

[32] Michael I. Pupin, *From Immigrant to Inventor* (New York, 1960), pp. 330–31. It is interesting that Pupin was issued two patents in May 1894 in which he proposed to extend greatly the possible range of transmission over telephone circuits by adding capacitors in series with the circuit conductors at periodic intervals. An abstract of his patents was published in *Electrical World,* along with an editorial which suggested that the proposed method might greatly reduce the cost of long-distance telephone circuits. The editor also pointed out that the invention might extend the possible distance of telephony, which seemed to have reached its practical limit in the recently completed circuit from New York to Chicago. The patents included the claim that the proposed method might even permit transatlantic telephony. See *Electrical World* 23 (1894):666, 678–80.

The publication of the claims in Pupin's patents stimulated a critical editorial in the British journal, *Electrical Review.* This editorial stated that the method proposed by Pupin was not new and was based on fallacious reasoning. It predicted that a test of the invention on an artificial cable would be sufficient to demonstrate that it would not achieve the effect claimed by Pupin (see a digest of this editorial in ibid., p. 873). The critical comments of the British editor in turn stimulated an editorial in *Electrical World* entitled "Criticism vs. Abuse." The editor argued that Pupin had at least given a very logical discussion in support of his proposal and that, even if his reasoning were fallacious, his claims should not be dismissed so arbitrarily without some definite evidence to refute his suggested method (see ibid., p. 824). This brought another response from the editor of the *Electrical Review,* who pointed out that experiments which had previously been carried out by engineers of the British Post Office had shown that the invention proposed by Pupin had an effect exactly opposite to that which he predicted (see *Electrical World* 24 [1894]:97). Pupin made no mention of these events in his book, which seems somewhat surprising because his suggested capacitor loading arrangement was ostensibly intended to achieve the same improvement in transmission as coil loading. In any event, nothing more was heard of capacitive loading after 1894.

mental tests related to loading shortly after returning to his laboratory at Columbia but had dropped the project in order to experiment with X-rays soon after hearing reports of Roentgen's discovery. Pupin wrote that he had suffered a nervous breakdown in the spring of 1896 following the death of his wife but had been able to resume work on the loading coil later the same year. His account gave no details of this work other than a statement that he had used apparatus which had enabled him to conduct experiments without using actual telephone circuits. Pupin also referred to a paper which he had read at a meeting of the American Institute of Electrical Engineers early in 1899, a paper which had been devoted to the theory of his apparatus but which had contained no explicit mention of loading. Pupin continued that his friend Cary T. Hutchinson, a consulting engineer, had approached him in October 1899 concerning the technical feasibility of designing an underground cable from New York to Boston for an independent telephone company. In his autobiography, Pupin wrote that he had expressed a willingness to design such a circuit, "guaranteeing to employ a wire not bigger than in ordinary cables capable of operating satisfactorily over a distance of only twenty miles." It was at that time, Pupin stated, that he had decided to apply for a patent on loading.[33]

Pupin's account contained no explicit mention of Campbell, but he alluded to the priority conflict:

> There were others besides Hutchinson, who had recognized that in my communication to the American Institute of Electrical Engineers there was hidden an invention for which telephone engineers had been eagerly waiting ever since the birth of the telephone art. This created an interference in the Patent Office which annoyed me, but not nearly so much as I had been annoyed there before. About a year from the date of my application for patent, the American Telephone and Telegraph Company acquired my American patent rights, treating me most generously. It gave me what I asked.[34]

[33] Pupin, pp. 332–37.

[34] Ibid., pp. 337–38. The earlier interference which Pupin mentions in this passage was a three-way contest between Pupin, John S. Stone of the American Bell Telephone Company, and two French applicants, Hutin and Leblanc. This dispute had involved a proposed method of transmitting several messages simultaneously over a single circuit with separation to be achieved at the receiving end by means of resonant circuits. Although hearings in this interference began in 1896, the final decision, which awarded the priority to Pupin, was not reached until 1902. Somewhat ironically, the method proposed proved to be impractical until after the development of electronic amplifiers and the discovery of a new type of wave filter by G. A. Campbell. The first successful system, which became known as multiplex or carrier telephony, was not placed in operation until 1918. See Julian Blanchard, "A Pioneering

Pupin went on to discuss the great impact which his invention had had on the public, the scientific community, and the telephone industry. He gave some credit to the Bell system for having exploited the loading coil successfully, but he added another somewhat condescending reference to the Boston laboratory:

> Twenty-five years ago the American Telephone and Telegraph Company had a small laboratory in Boston, where it did all its scientific research and development. But, presently, faultfinders like my invention moved into the peaceful and drowsy precincts of that tiny laboratory, and stirred up the engineers and the board of directors. I am very happy whenever I think that, possibly, my inventions have contributed some to this healthful stirring up. What was the result? To-day the American Telephone and Telegraph Company and the affiliated Western Electric Company employ about three thousand persons at an expenditure of some nine million dollars annually in their research and development work.[35]

In addition to an absence of experimental and theoretical details of his work on loading, Pupin's version of the invention and its development gives a distorted estimate of the actual impact of his personal contribution and omits many significant historical details brought out in the interference proceeding. It is therefore necessary to consider other evidence in order to achieve a more objective view regarding Pupin's role in the introduction of loading in telephony.

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There were important qualitative differences in both the experimental and theoretical contributions of Campbell and Pupin insofar as their influence on the eventual commercial success of loaded telephone circuits was concerned. For example, Pupin did no experimental work on actual telephone circuits comparable with the dramatic and convincing Pittsburgh cable tests performed by Campbell. It is clear that Pupin and some of his students at Columbia conducted intermittent experiments using artificial transmission lines during the years 1895–1900. However, it seems quite doubtful whether these experiments were recognized as being relevant to the loading problem before late in 1899.[36] The paper

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Attempt at Multiplex Telephony," *Proceedings of the IEEE* 51 (1963):1706–9; and E. H. Colpitts and O. B. Blackwell, "Carrier Current Telephony and Telegraphy," *Trans. AIEE* 40 (1921):205–300.

[35] Pupin, p. 340.

[36] The problem of evaluating the work before 1899 is complicated by the fact that an artificial line designed to simulate an ordinary telephone circuit or to simu-

which Pupin read early in 1899, in which the loading invention was supposedly "hidden," contained a mathematical analysis of an artificial line having *n* identical sections. In this paper, he sought to determine the conditions under which such an arrangement would "become equivalent with sufficient approximation to a uniform transmission line when n is not infinitely large."[37] The experimental results reported in the paper included only wave length and propagation velocity measurements, not attenuation. Pupin admitted that the leakage factor of the apparatus was much greater than that of a normal circuit. Since this would have made the attenuation much greater as well, it is probable that loading experiments would have been inconclusive even if attempted with this apparatus.[38]

Charles S. Bradley, who was not mentioned in the account of the invention in Pupin's book, was one of Pupin's more important witnesses in the interference proceeding.[39] Pupin testified that he had discussed the loading invention with Bradley shortly after the presentation of the March 1899 paper.[40] In addition to supporting Pupin's testimony on this point, Bradley stated that he had then attempted to interest the General Electric Company in the loading coil but without success. None of the General Electric officials mentioned were questioned during the proceeding.[41] And Pupin's behavior during the months following his con-

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late a loaded telephone circuit would appear substantially the same insofar as its constructional features are concerned. Pupin was unable to establish that any of his theoretical or experimental work prior to 1899 had been on the problem of coil loading and had not merely been intended to determine the conditions under which normal telephone circuits could be adequately simulated by artificial lines.

[37] M. I. Pupin, "Propagation of Long Electrical Waves," *Trans. AIEE* 16 (1899): 120.

[38] Pupin attempted to demonstrate the effect of coil loading using one of his artificial lines in May 1901 during the interference hearings. The results were apparently erratic and marginal. See *RGAC*, p. 49; see also the patent examiner's decision of December 9, 1903 in the U.S. Patent Office file for Interference no. 20,699, pp. 70–72.

[39] In 1899 Bradley was president of the Ampere-Electric Chemical Company, with Pupin serving as one of the company directors. See the *Record for M. I. Pupin*, 2 vols., Interference no. 20,699 (Washington, D.C., 1902), 1:288 (hereafter cited as *RMIP*). Bradley had also founded the Bradley Electric Power Company to exploit his rotary converter but had sold out to General Electric in 1893. See W. Paul Strassmann, *Risk and Technological Innovation: American Manufacturing Methods during the Nineteenth Century* (Ithaca, N.Y., 1959), p. 167.

[40] *RMIP*, 1:76.

[41] Ibid., p. 291. Why the General Electric Company rather than a telephone company should have been approached was never made clear. The fact that Bradley had been concerned primarily with the technology of electrical power rather than

versation with Bradley does not indicate that he felt the sense of urgency which might be expected of a man in possession of a potentially valuable technological innovation. The available evidence seems to support the view that Pupin did not undertake to work out the necessary theoretical conditions for loading or to obtain experimental evidence that loading would actually improve transmission quality even on artificial lines until after he was approached by Cary T. Hutchinson late in 1899.

Hutchinson, retained as a consultant by the Telegraph, Telephone, and Cable Company of America to provide technical advice on a proposed underground cable between New York and Boston, requested an interview with Pupin to discuss the problem.[42] Pupin later testified that he had offered to design a loaded cable circuit and also to demonstrate its feasibility using an artificial line if Hutchinson's clients were willing to pay for its construction. The company had agreed to pay up to $5,000 to support Pupin's proposed experimental demonstration. Pupin stated that he had begun preparations for the demonstration but had subsequently broken off negotiations and had decided to continue preparations for the experiment at his own expense. He gave as his reason that he had decided that Hutchinson's clients were attempting to gain control of the loading invention for an inadequate sum.[43] The aborted negotiations and the concurrent calculations which Pupin carried out seem to have been decisive stimuli in causing him to realize the potential value of loading in telephony and to undertake to obtain a patent on it.[44] Pupin stated that he had contacted his attorney on the

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with electrical communications suggests that Pupin and Bradley might have been thinking in terms of a method for improving the efficiency of power transmission. If so, this would in itself be evidence that Pupin had not yet gone beyond the qualitative stage, since the later theoretical work of both Pupin and Campbell clearly demonstrated that loading was of no practical value in power transmission.

[42] The Cable Company was one of a group organized in 1898–99 for the purpose of forming a national system of circuits to compete with the Bell system. The attempt soon collapsed despite substantial capitalization. See J. W. Stehman, *The Financial History of the American Telephone and Telegraph Company* (New York, 1967), pp. 57, 81. Hutchinson was acquainted with Pupin through their activities in the American Institute of Electrical Engineers. Hutchinson was aware of Pupin's interest in telephony and could, of course, expect no assistance from Bell system engineers.

[43] *RMIP*, 1:85.

[44] Although it is possible that Pupin may have learned of Campbell's loading tests on the Pittsburgh cable a month before, there seems to be no convincing evidence of stimulus diffusion in this case.

matter in November and had spent the remaining time before the filing date in December in explaining the invention to the attorney and in helping to write the specifications.[45]

Pupin's patent application contained his so-called sine rule, which Pupin called "the foundation upon which the invention described in this application rests."[46] The rule stated that the degree of equivalence between a coil-loaded line and a uniform line having the same total self-induction and other parameters could be determined by comparing the quantities sin $\phi/2$ and $\phi/2$ of the loaded circuit. The angle ϕ was defined as the angular or radian interval between coils expressed as a fractional part of a wavelength. For cases which the rule indicated to be sufficiently equivalent, one could employ Heaviside's equations for a uniform line to compute the attenuation and other properties of the loaded circuit. For example, if a line were loaded with ten coils per wavelength at a given frequency, one half of the radian interval would be 0.314 or 18 degrees. Since the sine of 18 degrees is 0.309, the rule would predict that the error involved in using the Heaviside uniform line equations to calculate the performance of the loaded circuit would not exceed 1.6 percent. The patent application did not include a derivation of the sine rule.

Two weeks after filing the patient application, Pupin presented a paper on the mathematical theory of transmission circuits at a meeting of the American Mathematical Society.[47] The paper included an analysis of three different transmission structures. These were a uniform transmission line, a "non-uniform conductor of the first type," and a "non-uniform conductor of the second type." Pupin pointed out that he had previously published an analysis of the first two structures in his March 1899 paper in the *Transactions of the American Institute of Electrical Engineers* but that his analysis of the third structure was new.[48] A nonuniform conductor of the first type was simply an artificial transmission line, but a nonuniform conductor of the second type was an actual telephone circuit with identical loading coils inserted at equal intervals along the circuit. Pupin stated that the principal aim of the paper was to determine the "conditions under which a non-uniform conductor of the second type is approximately equivalent to its corresponding

[45] *RMIP*, 1:86. Pupin's attorney, Thomas Ewing, later became the commissioner of patents. See Vaughan, p. 292.

[46] See a file wrapper included in *RMIP*, 1:2.

[47] M. I. Pupin, "Wave Propagation over Non-Uniform Electrical Conductors," *Transactions of the American Mathematical Society* 1 (1900):259–86.

[48] Ibid., p. 261.

uniform conductor."[49] He then proceeded to derive the sine rule which gave the degree of approximate equivalence.[50]

Pupin's loading-coil analysis was first brought to the attention of the electrical engineering profession when he read a paper at a meeting of the American Institute of Electrical Engineers in May 1900. The paper included the theoretical material from his earlier papers before the American Mathematical Society and, in addition, some experimental results obtained on a recently constructed artificial line.[51] He also reported that he had used telephone apparatus provided for him by the New York Telephone Company, a Bell system operating company.[52] By way of contrast, Campbell had carried out similar tests approximately a year earlier and had loaded an actual telephone cable eight months earlier. Campbell had also designed the loaded circuits which were opened for public use the day before Pupin's paper was read on May 19.[53]

Pupin's claims in the patent application were initially rejected by the patent examiner, who cited the earlier patents of Silvanus P. Thompson and John S. Stone.[54] Pupin then filed an amendment and

[49] Ibid., p. 275.

[50] This paper does not seem to have stimulated any comment in engineering journals, so the effective disclosure of his loading theory to the electrical engineering profession was delayed until his paper was read before the American Institute of Electrical Engineers in May 1900.

[51] M. I. Pupin, "Wave Propagation over Non-Uniform Cables and Long Distance Air-Lines," *Trans. AIEE* 17 (1900):445–507. See also the discussion of his paper in ibid., pp. 508–13, and an editorial about it in *Electrical World and Engineer* 35 (1900):773–74.

[52] Pupin, "Wave Propagation over Non-Uniform Cables and Long Distance Air-Lines," p. 472. There was apparently little coordination between work in New York and that carried out by the staff of the Boston laboratory. It is doubtful whether the engineers of the Bell affiliates in New York were yet aware of Campbell's success in loading the Pittsburgh cable or the experiments which were in progress on circuits in the Boston area. If they were aware of the success achieved by the Boston engineers, it is difficult to understand their interest in supporting Pupin except perhaps in the context of the existence of a degree of rivalry between the Bell engineers in New York and Boston.

[53] *RGAC*, pp. 58–59.

[54] See n. 11 above. Thompson had read a paper at the Chicago meeting of the International Electrical Congress in 1893 suggesting that the use of periodic coils in shunt with underwater cables might compensate for cable capacitance and make transatlantic telephony possible. Thompson was granted four patents on "compensated cables" between 1891 and 1894. The American rights to his patents were purchased by the American Bell Telephone Company, but the use of shunt coils for compensation never became a practical success. See Silvanus P. Thompson, "Ocean Telephony," *Electrician* 31 (1893):474. Also, see J. A. Fleming, pp. 133–41.

a written argument in support of patentability. The examiner again rejected his claims and added a reference to Heaviside's papers. Pupin replied with an argument which emphasized the importance of relating the coil spacing to the wavelength of the transmitted signals. In a letter dated May 12, 1900, the examiner, in effect, accepted Pupin's argument but also informed him of a possible interference with the claims of another applicant. In a later letter, the examiner requested that Pupin divide his claims into two groups, since all of them could not be allowed in a single application. Pupin complied with this request and was then notified that the applications were being sent to issue. Pupin was issued two loading patents on June 19, 1900. An announcement of an interference with the still pending applications of Campbell followed in August.[55]

Meanwhile, Campbell, whose application had been filed in March, received notification that his claims were being rejected, based on a reference in Heaviside's papers. He made no immediate reply and received another letter from the examiner on May 12 which informed him of a possible interference if his claims were found patentable. Campbell was given ten days to respond, with the warning that if he failed to do so, the application of the rival claimant would be sent to issue. The deadline was allowed to pass without response.[56] An amendment and an argument in support of patentability were finally filed in Campbell's behalf late in June. The examiner then notified him that loading patents had already been issued to Pupin. In August, Campbell filed another amendment and three affidavits in support of his application. He was thereupon notified that the priority of invention would be determined by an interference proceeding.[57]

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There were a number of interesting developments long before a final decision was reached in the interference proceeding early in 1904. W. W. Swan, the Bell patent attorney, had written to the company president, John E. Hudson, in the summer of 1900 to express

[55] See a file wrapper included as an exhibit in *RMIP*, 1:32–53. The patents issued to Pupin were nos. 652,230 and 652,231.

[56] The responsibility for handling the case was in the hands of the Bell patent attorney, with Campbell acting primarily as a technical consultant. The failure to respond to the examiner before the deadline was never explained. This placed Campbell at a greater disadvantage than if both applications had still been pending. Since Campbell became the junior contestant, Pupin and his attorney were able to read Campbell's deposition before preparing Pupin's brief.

[57] *RGAC*, pp. 273–93.

the belief that patents might be issued to both Pupin and Campbell without an interference being declared. Swan suggested that, in that event, it would be in the company's best interest to control both patents. However, since it was uncertain whether either man's patents could be successfully defended if contested, because of previous patents and publications on loading, Swan recommended that provision be made to give yearly payments to Pupin only so long as his patents should remain undefeated. Hudson thereupon decided to obtain an option on the patents, and Pupin was given an initial sum of $15,000 in October 1900.[58] The option was exercised the following January with Pupin receiving an additional payment of $185,000 despite the fact that the first testimony had not yet been taken in the interference proceeding.[59]

Following extensive testimony on behalf of each claimant, the examiner's decision favoring Pupin was handed down in December 1903.[60] The Bell company president, Frederick P. Fish, then contacted Campbell to request that he read over the examiner's decision and give advice on what further action the company should take. Fish

[58] A copy of the letter from Swan to Hudson and a number of other letters and documents related to the activities of Hammond V. Hayes and other members of the staff of the Boston laboratory are contained in the files of Professor Edward L. Bowles of Wellesley Hills, Mass. (hereafter cited as Bowles file). I am indebted to Professor Bowles for permitting me to examine this material. John Hudson died suddenly on October 1, 1900. Alexander Cochrane served as president pro tem until Frederick P. Fish, an eminent patent lawyer, was selected as the new president on July 1, 1901.

[59] According to extracts from Pupin's contract in the Bowles file, Pupin continued to receive annual payments until 1917 for a total of $455,000. Pupin also agreed to assign to the Bell system any other inventions which he might make related to loaded circuits. Reports in the technical press at the time varied widely on the amount received by Pupin for the rights to his patents. See, for example, *Electrician* 46 (1900):454, 532. The editor pointed out that Pupin was only following the suggestions made by Heaviside and expressed surprise that it had taken so long to submit them to a practical test. The editor wrote that the great financial reward received by Pupin might finally lead engineers to pay more attention to the results of mathematical analysis even though the details of Heaviside's theoretical work had been beyond the comprehension of most of them. Pupin was granted a loading patent in Germany in 1904 after extended tests and hearings. He sold the right to this patent to the Siemens and Halske Company. See *Electrical World and Engineer* 43 (1904):324. For an account of Pupin's negotiations with Siemens and Halske, see George Siemens, *History of the House of Siemens*, trans. A. F. Rodger, 2 vols. (Freiburg, 1957), 1:178–81.

[60] The decision gave Pupin a disclosure date of March 22, 1899 and Campbell a disclosure date of March 24, 1899. See the examiner's decision of December 9, 1903, pp. 11, 21.

stated that it was his wish that "there should be no cloud upon the title of the successful contestant."[61] Apparently, Campbell recommended that the matter be pursued, since the examiner's decision was appealed to the board of examiners-in-chief in January. The board's decision was handed down in April and also awarded priority to Pupin. The board decision might then have been appealed to the patent commissioner and, if necessary, to a federal appeals court. However, Fish decided against further action in the case, leaving Pupin the legal winner.[62]

In examining the basis for the decision favoring Pupin's priority, it appears that the strategy of Pupin and his attorney was to concentrate attention on Pupin's early work on "non-uniform conductors of the first kind," or artificial lines. They were able to take full advantage of the superficial similarity of this structure to the loaded circuits which Pupin astutely called "non-uniform conductors of the second kind." There is no convincing evidence that Pupin began either theoretical or experimental work related to the latter structure until after his interview with Hutchinson in October 1899. It is perhaps not surprising that the patent examiner failed to grasp the crucial difference between the two structures in view of the conflicting testimony of the expert witnesses in the case. The notoriety achieved by Pupin following the sale of his patent rights for such an impressive sum may also have helped to cloud the issue and increased the tendency to give Pupin the benefit of any remaining doubts.[63]

[61] Fish to Campbell, December 18, 1903, Bowles file.

[62] Campbell wrote a memorandum on the matter in 1911 in which he stated that Fish had informed him that the decision not to appeal to the commissioner was based on Fish's belief that the commissioner was not only likely to render a decision against Campbell but might even declare the invention to be unpatentable. The reason given for the commissioner's probable prejudice was that Fish had previously declined to recommend the commissioner for his position. A copy of Campbell's memorandum is in the Bowles file.

[63] Pupin was even given public credit for the invention by John J. Carty, a leading Bell engineer, at a meeting of the American Institute of Electrical Engineers in 1902 several months before the interference was settled. See *Trans. AIEE* 19 (1902): 411–12. Carty had also supported Pupin in 1900 in an abortive attempt by a dissident group in the American Institute of Electrical Engineers to elect Pupin as president of the institute instead of the official nominee, Carl Hering. See a letter from Carty in *Electrical World and Engineer* 35 (1900):709. The campaign to elect Pupin took the form of a letter, circulated among the members, which repudiated the official slate chosen by the institute council and solicited votes for Pupin. See ibid., pp. 591–92. The dramatic coincidence which might have occurred if Pupin had been elected as the new president of the institute at the annual meeting in May, where he also read his paper disclosing his work on loading, was averted when he was de-

The favorable decision in the interference proceeding further enhanced Pupin's image as a great inventor and exemplar of American opportunity for immigrants. Despite this, the evidence strongly suggests that Campbell's contributions were actually much more influential insofar as their direct impact on communications technology is concerned. Campbell's theoretical analysis of loading was more exact than Pupin's and also proved more applicable in practice. The loading graphs which Campbell prepared for his July 1899 report were in the form needed by engineers in making practical decisions on loading, while Pupin's work produced nothing comparable. Pupin's famous "sine rule" was an approximation giving results which were least accurate for the maximum allowable coil interval, the case where maximum accuracy was needed.[64] Because of his great concern with the problem of establishing the degree of equivalence between loaded circuits and a fictitious uniform line having the same electrical parameters, Pupin also overlooked the important discovery made by Campbell of the cutoff phenomenon.[65] This became the basis of Campbell's later work on the electric wave filter, a key innovation in 20th-century electrical technology.[66] Finally, there seems no question that Campbell was the first to demonstrate loading on an actual telephone circuit and that he and his assistants were already in the process of exploiting the discovery commercially before Pupin's work was disclosed.

It does seem probable that loading could have been introduced on the basis of Pupin's theory if Campbell's work had not already been available. However, in that case the introduction of loading would have been considerably delayed and would have led to somewhat different procedures than were actually used. In particular, more coils per wavelength would have been indicated, with a considerable increase in loading costs, if Pupin's sine rule rather than Campbell's

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feated by a vote of 381 to 179. See ibid., p. 791. Apparently, the faction supporting Pupin's candidacy was motivated at least in part by opposition to proposed changes in the institute constitution, changes which would, among other things, limit the rights of associate members to hold office. See ibid., p. 709. Presumably as a consequence of the "independent" campaign of 1900, the "gentleman's agreement" that Pupin would be the official candidate the following year was not carried out, although he was finally elected president of the institute in 1925. See ibid., p. 592.

[64] For a comparison of results predicted by Campbell's equation and by Pupin's sine rule, see Fleming, pp. 130–31.

[65] See n. 21 above.

[66] See J. D. Tebo, "George A. Campbell, 1870–1954," *Bell System Technical Journal* 34 (1955):1–4. Also, see Lloyd Espenschied, "The Electric Wave Filter," *IEEE Spectrum* (August 1966), p. 162.

equation had been used as a guideline for engineers. Although it does not appear that Pupin's theoretical work had any significant influence on loading as practiced by the Bell engineers, the possession of the rights to his patents was of value in that it enabled the company to maintain an effective monopoly on loading until 1917. During their lifetime, the Pupin loading patents were probably the most important which the company controlled.

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The analysis of the events in the early history of loading in telephony suggests some more general conclusions of significance in the history of technology. This technical advance was symbolic in marking the appearance of a new type of "invention" and a new type of "inventor." Both contestants for legal priority were men with graduate-level training in mathematical physics. The theoretical aspects of loading were such that the necessary details for its successful introduction could not have been worked out by anyone not having a similar degree of analytical sophistication.

The rather procrustean nature of the patent system, which required that a single inventor be determined without the exercise of a value judgment on either the comparative quality or the influence of each man's work, has sometimes been, as in this instance, more conducive to legends than to accurate technological history. Furthermore, the general policy of secrecy which seems to have been followed in the Bell system at that time also tended to exercise a distorting effect on the professional reputation of its own research engineers. The apparent decision of the company management to give Pupin all of the public credit for the invention of the loading coil, while failing to publicize the many important contributions of the staff of the Boston research laboratory, may have seemed quite rational in the competitive situation in which the company then found itself. However, this policy tended to prolong the "heroic age of invention" and to postpone public realization of the rapidly growing importance of industrial research laboratories, staffed by graduate scientists and engineers. The introduction of loading might have become an early symbol of achievement of organized industrial research and development, but instead it became the basis of a persistent myth associated with the independent "immigrant inventor."